

## **Northern Indian Ocean Salt Transport (NIOST): Estimation of Fresh and Salt Water Transports in the Indian Ocean using Remote Sensing, Hydrographic Observations and HYCOM Simulations**

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### **LONG-TERM GOALS**

Ocean salinity is one of the most important variables in oceanic and climate studies. Together with temperature they regulate the density of ocean water and are used to determine the formation of water masses and circulation. Whereas temperature has been measured very extensively in the world's oceans by both *in-situ* and remote means, salinity observations are very limited and not uniformly distributed geographically; they are mainly confined to shipping lanes and the summer season. Consequently, basin wide oceanic processes, air-sea interaction and climate studies that require the incorporation of salinity data are quite a challenge. In the Indian Ocean where seasonal reversals of winds lead to reversal of ocean currents and transport processes, salinity shows very wide variability. It is therefore important to understand the dynamics of exchange of salt in this Ocean, especially when net fresh water flux is seasonally different in the various basins of the ocean. Such ocean-wide studies have been limiting in the past as a result of the lack of basin-wide salinity data. Though ocean salinity is one of the most important variables in the oceanic and climate studies, a gap in the Indian Ocean observing system to date has been the scarcity of surface salinity data. This study involves the use of high resolution (1/12°) HYbrid Coordinate Ocean Model (HYCOM) numerical model and salinity derived from satellites (SMOS and Aquarius Salinity missions), hydrographic data, and Argo floats to understand the freshwater and salt transport dynamics in the Indian Ocean.

This preliminary study, in 5 months, emphasizes that HYCOM sea surface salinity is a good proxy to compare the satellite-derived salinity. Additionally, the study on long-term salt transport (2003-2012) reveals seasonal reversal in the mean salt transport which is more pronounced in the northern Indian Ocean. On interannual scale, the Indian Ocean Dipole and El Niño Southern Oscillation events also influence salt transport variability. This study also analyzes the critical role of salinity in the formation of the Arabian Sea mini warm pool using Soil Moisture and Ocean Salinity (SMOS), Aquarius salinity missions, HYCOM and Argo float data.

### **OBJECTIVES**

1. To estimate near surface salt transport using satellite and *in situ* salinity observations and compare with HYCOM simulated near surface salinity fields, and obtain depth- integrated salt transport from HYCOM.

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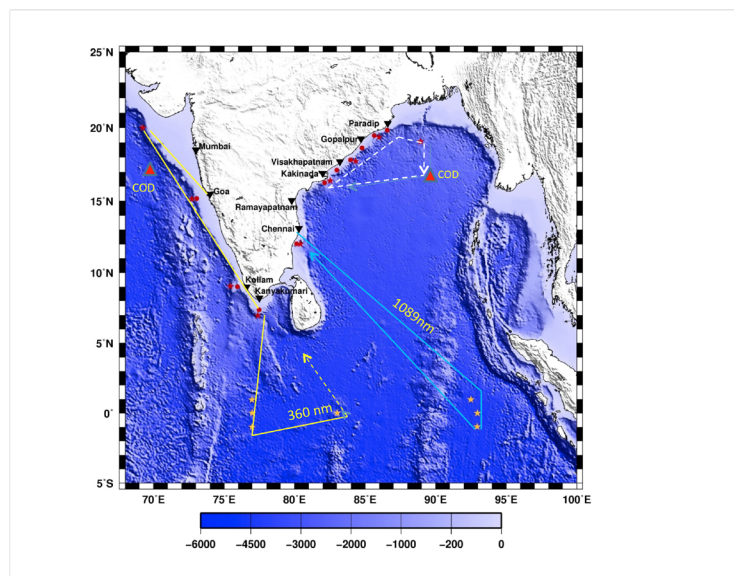
2. To address the salinity variability at intraseasonal, interannual and decadal time scales and its impact on the circulation and particularly the coastal currents.
3. To study of role of salinity on the barrier layer dynamics in the Bay of Bengal (BoB), Arabian Sea (AS) and Equatorial Indian Ocean (EIO).
4. To study the role of the coastal Kelvin waves on the fresh and salt water transports.

## APPROACH

In this study, monitoring of Sea Surface Salinity (SSS) from space, combined with regular surface and sub-surface salinity profiles from *in situ* observing systems (surface ships, buoys, and the Argo array, surface flux moorings and shipboard surveys) and high resolution ( $1/12^\circ$  HYbrid Coordinate Ocean Model; HYCOM)) simulations (1993 - present) are used to investigate seasonal variability of salinity and fresh water transports in the northern Indian Ocean to understand the balance of freshwater input over the northern and equatorial Indian Ocean. Several cruises are proposed to collect surface and subsurface salinity in the BoB, AS and in the Equatorial Indian Ocean (EIO) to estimate fresh and salt water transports.

## WORK COMPLETED

This project was started on 1 May 2012, in these 5 months we did an excellent progress. We have published two journal articles. We have completed one cruise in the Bay of Bengal (as shown in figure) so far and the data will be analyzed soon. We processed all available SMOS (December, 2009-present) and Aquarius salinity (August, 2011-Present) missions' data, and Argo floats data. We are obtaining the HYCOM simulations in near-real time daily data (2003-present).



\* Deep-Sea ADCP  
Equatorial moorings

Δ Shallow water ADCP  
moorings

— Cruise track

COD Bio-geochemical  
mooring station and  
sediment trap mooring.

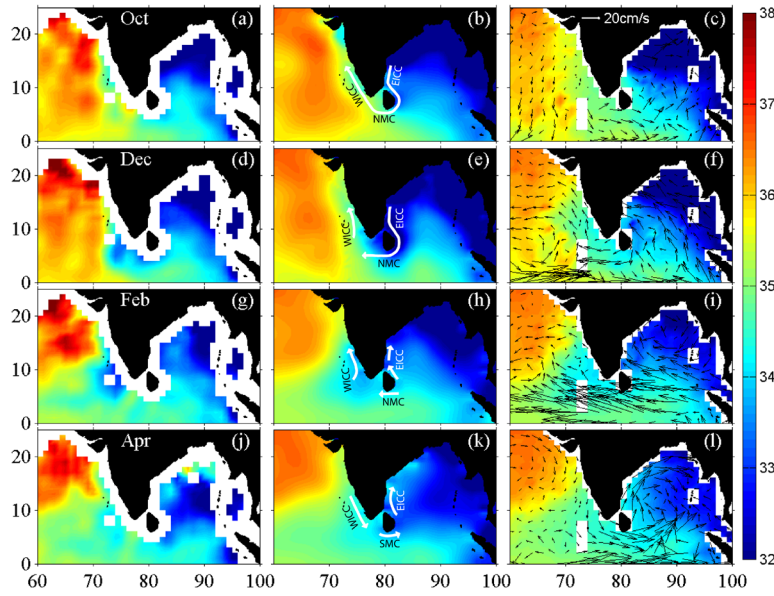
Cruise track in the Indian Ocean. Cruises are conducted annually to deploy moorings (2012 Apr-2015 March). Cruise tracks in BoB (Apr-May), Arabian Sea (Oct-Nov) and Equatorial Indian Ocean (Jan-Feb).

## RESULTS

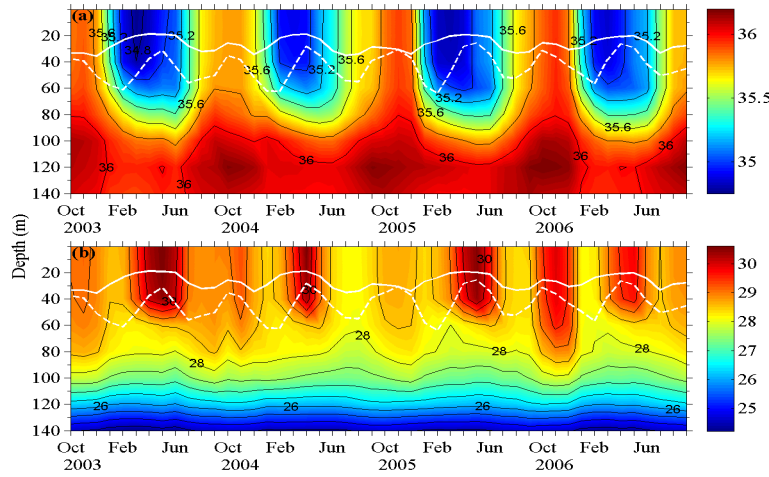
### *(1) The Role of Salinity on the dynamics of the Arabian Sea mini warm pool*

Warmer ( $>28^{\circ}\text{C}$ ) Sea Surface Temperature (SST) occurs in the South Eastern Arabian Sea (SEAS,  $5^{\circ}$ - $13^{\circ}\text{N}$ ,  $65^{\circ}$ - $76^{\circ}\text{E}$ ) during March-April, and is known as the Arabian Sea Mini Warm Pool (ASMWP). In this study, we addressed the role of salinity and the upper layer heat and salt budgets in the formation and collapse of this ASMWP. An assessment of Sea Surface Salinity (SSS) data from the Soil Moisture and Ocean Salinity (SMOS) satellite mission for the year 2010 showed that SMOS is able to capture the SSS variability in the SEAS (Figure 1). Analysis of temperature, salinity and currents from the HYbrid Coordinate Ocean Model (HYCOM) during 2003-06, and, *in-situ* temperature and salinity data from Argo floats during 2003-06 for the SEAS revealed that low salinity waters cap the top 60 m of the SEAS in January-February (Figure 2 and 3). This minimum salinity was concurrent with the formation of a barrier layer and with the time when the SEAS gained little net heat flux and the equatorward flowing East India Coastal Current (EICC), from the Bay of Bengal, fed low saline waters into the SEAS. Subsequently, the net heat flux increased to a peak value under the increased salinity stratification, leading to the formation of the ASMWP in March-April. The ASMWP collapsed by May due to increase in SSS and the associated weakening of the salinity stratification. The monsoon onset vortex in May 2004 could be related to the minimum SSS that occurred in February 2004, followed by higher SST and heat content of the ASMWP in April 2004.

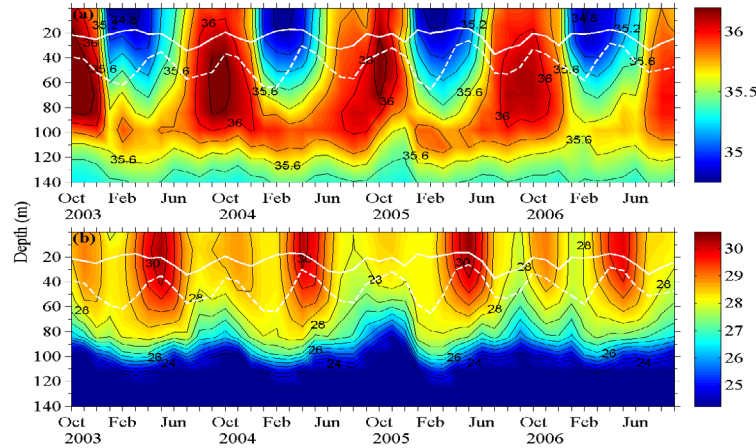
We have examined the mixed layer heat budget and salt budget for 2003-2006 from HYCOM simulations and Argo data and identified the contributions of horizontal advection of low salinity waters into the SEAS during winter months (February) as a precursor to development of the intense warm pool after 2 months (April) due to dominant surface heat fluxes. The upper ocean heat content in the salinity-stratified layer contributes largely to the formation of the monsoon onset vertex and this is well evidenced in the case of monsoon onset vertex in May 2004. This impact on the SST in the ASMWP impacts the upper ocean heat content in the salinity-stratified layer, which then affects the variability of (formation or absence) of the monsoon onset vertex over the SEAS, prior to the southwest monsoon.



**Figure 1.** Selected monthly maps of sea surface salinity (SSS) for SMOS (left column; a, d, g and j), Argo (middle column; b, e, h and k) and HYCOM (right column; c, f, i and l; superimposed with HYCOM near-surface currents) for October, December, February, and April 2010. The white arrows (in the middle column figures) show a schematic of the pathways of the major currents in the region: EICC, the East India Coastal Current, WICC, the West India Coastal Current, NMC, the Northeast Monsoon Current and SMC, the Southwest Monsoon Current.



**Figure 2.** Depth-time sections of SEAS box-averaged (a) HYCOM salinity and (b) HYCOM temperature during October 2003 – September 2006 for the SEAS region. The mixed layer depth (solid white line) and isothermal layer depth (dashed white line) are overlaid. Contour interval is 0.2 psu and 0.5°C respectively for salinity and temperature.



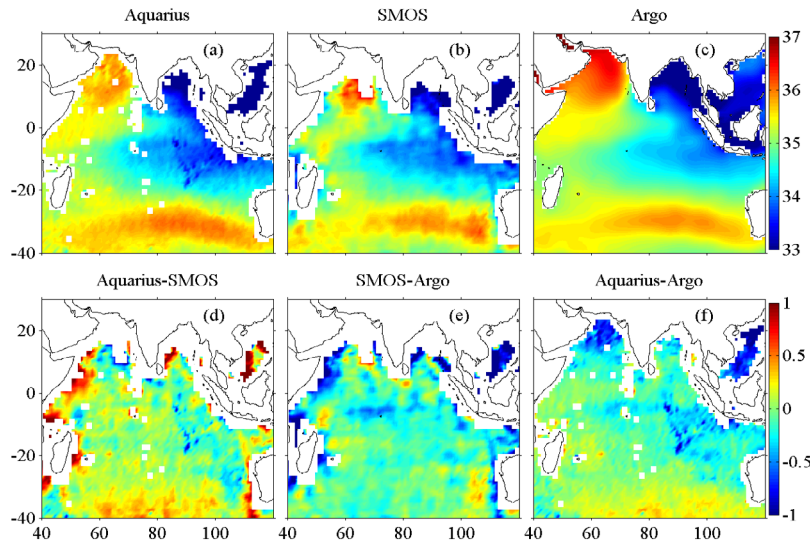
**Figure 3. Depth-time sections of SEAS box-averaged (a) Argo salinity and (b) Argo temperature during October 2003 - September 2006 for the SEAS region (see white box in Figure 1). The mixed layer depth (solid white line) and isothermal layer depth (dashed white line) are overlaid. Contour interval is 0.2 psu and 0.5°C respectively for salinity and temperature.**

## **(2). Preliminary SMOS and Aquarius Salinity measurements and Validation**

Global Sea Surface Salinity (SSS) measurements retrieved from the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission are the first highest resolution salinity data available from space. There are many challenges to measuring salinity from space and obtaining a targeted accuracy of 0.1 psu. Comparisons of Level 2 (L2) SMOS SSS data with the 1/12° high resolution HYbrid Coordinate Ocean Model (HYCOM) simulations of SSS reveal large differences. These differences are minimized for an extent during the creation of Level 3 (L3) SMOS data through spatial and temporal averaging. Depending on the retrieval algorithm used, there are differences between ascending and descending passes with data collected during the descending pass exhibiting a bias towards lower SSS. It is challenging to process SMOS SSS data in the northern Indian Ocean due to Radio Frequency Interference (RFI) and large seasonal variability due to monsoonal circulation. Comparisons of SMOS L3 data with Argo float SSS and HYCOM SSS indicate the lowest discrepancies in SSS for these data sets occur in the southern tropical Indian Ocean and the largest differences between the compared salinity products are noticed in the Arabian Sea and Bay of Bengal with an erratic root mean square error in the latter region. Higher errors in SSS occurred in coastal areas compared to the open ocean. The accuracy of SMOS salinity measurements is increasing with the maturity of the data and new algorithms.

The Aquarius salinity mission is currently providing global coverage of sea surface salinity (SSS) measurements every 7 days. In this study, we assess the validity of preliminary Aquarius salinity measurements in the Indian Ocean by comparing it to the Soil Moisture and Ocean Salinity (SMOS) mission SSS, Argo float SSS data and the 1/12° high resolution HYbrid Coordinate Ocean Model (HYCOM) SSS output (Figure 4). Comparisons of Aquarius passes with HYCOM, SMOS, and Argo indicate Aquarius is performing better than the SMOS mission for daily measurements. Analysis of monthly Aquarius data with other SSS measurements indicates Aquarius is highly correlated with HYCOM and Argo in the open ocean and on average, the differences in SSS rarely exceed above 0.4

psu at this temporal resolution. Aquarius SSS is able to capture the salinity features in the Indian Ocean. Notably are the high SSS in the Arabian Sea, low SSS in the Bay of Bengal and low salinity tongue from the Indonesian Throughflow (ITF). Aquarius is however not able to resolve SSS within close proximity to the coast. Comparisons between monthly Level 3 Aquarius SSS with SMOS show regional differences in excess of 1.0 psu. Boxed-averaged comparisons of salinity differences and root mean square error statistic suggest that the largest differences between the salinity products occur in the Bay of Bengal, possibly the consequence of high salinity variability, precipitation and river runoff in that region.



**Figure 4.** Level 3 SSS averaged for August 2011 to May 2012 for (a) Aquarius, (b) SMOS, and (c) Argo. The differences between the SSS products are shown for (d) Aquarius and SMOS, (e) SMOS and Argo and (f) Aquarius and Argo.

## IMPACT/APPLICATIONS

For Naval applications, understanding salinity transport in the Indian Ocean is relevant in the area of anti-submarine warfare. Salinity transport impacts density fronts and the depth of both the mixed layer and thermocline, which are important for acoustic performance predictions. The regions like the Bay of Bengal where freshwater occupies the top layer, the sound velocity profile will change and there will be acoustic losses. Internal waves can be generated due to the strong salinity stratification, and barrier layer formation occurs. Also, investigations on the ocean transport processes and their effects on the carbon flux fall within ONR's quest to understand "environmental evolution, assimilation of data, and the limits of predictability by planning, fostering and encouraging scientific inquiry and technological development in fields ranging from littoral geosciences to high latitude dynamics."

## RELATED PROJECTS

None

## PUBLICATIONS

- ***Refereed Publications***

- 1) Nyadjro, E.S., B. Subrahmanyam, V.S.N. Murty, J.F. Shriver (2012). Role of Salinity on the dynamics of the Arabian Sea Mini Warm Pool, *Journal of Geophysical Research*, 117, doi:10.1029/2012JC007978.
- 2) Subrahmanyam, B., G. Grunseich, E.S. Nyadjro (2012). Preliminary SMOS salinity measurements and validation in the Indian Ocean, *IEEE Transactions Geoscience and Remote Sensing*, 50, 12, doi:10.1109/TGRS.2012.2199122.

- ***Conference/Workshop presentations***

Subrahmanyam, B. (2012). Estimation of Fresh and Salt water transports in the Indian Ocean, 4<sup>th</sup> Argo Science workshop, September 27-29, 2012, Venice, Italy. (*Invited oral Presentation*).

## HONORS/AWARDS/PRIZES

(1) Ebenezer Nyadjro (Graduate student)

- ✓ Awarded 2012 Outstanding Dissertation Award.
- ✓ Awarded The National Academies/National Research Council (NRC)/ Research Associateship to work at NOAA/PMEL
- ✓ Awarded F. John Vernberg Best Publication Award
- ✓ Awarded USC Graduate Student Day oral presentation second prize.
- ✓ Awarded F. John Vernberg Outstanding Graduate Teaching award
- ✓ Selected as a participant in the Physical Oceanography Dissertation Symposium (PODS VII) held at Lihue, Kauai during October 7-11, 2012.

(2) Gary Grunseich (Graduate Student)

- ✓ Awarded Taber Award for Outstanding Masters Research in the Field of Geological Sciences